Analysis of the deep hole drilling with BTA system by the characterization of the cutting process

Analyse du procédé de forage profond avec système BTA par la caractérisation du processus de coupe

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Abstract:

This paper deals with the analysis of the cutting process in the BTA (Boring Trepanning Association) deep hole drilling. The process is used when the machining with a conventional tool is not possible. Poor training and/or poor chips evacuation often cause a temperature rise and excessive wear which affect the dimensional stability of machined parts. The process is relatively not explored enough, because it is difficult to instrument experimental tests (measurement of cutting forces and temperature at each insert…). The thermomechanical phenomena are localized at the end of the BTA drilling head and confined in a zone inaccessible to the observation. Hence, a study of this process has been proposed. The evaluation of the chips morphology has been performed. Indeed, it is a good indicator of the stability of the cutting process and it can therefore be a serious help in the selection of optimal cutting parameters. Adequate parameters are proposed to highlight the impact of cutting conditions on the cutting process. Macro and microscopic observations of generated chips under several cutting conditions are performed. Fragmentation and segmentation of chips are some examples of analyzed phenomena. In this sense, experimental tests have been conducted. The chips have been sorted according to their morphology and identified according to their origin and then proposed physical parameters are assessed. The quantitative and qualitative analysis of chips allowed identifying the impact of the cutting speed and feed rate on the cutting process.

Keywords: **BTA deep drilling, drilling, chips morphology/fragmentation, quantitative analysis**

Résumé :

Cet article concerne l'analyse du processus de coupe on perçage profond avec system BTA. Le procédé est utilisé quand l'usinage avec des outils conventionnels (hélicoïdaux) de perçage n'est pas possible. Un mauvais guidage de l'outil ou une mauvaise évacuation des copeaux souvent entraine une usure excessive de l'outil, réduisant ainsi sa durée de vie et une instabilité dimensionnelle sur la pièce. Le procédé est peu étudié, car il est difficile d'instrumenter les essais de forage (mesures d'efforts et de température…). De plus, les phénomènes thermomécaniques liés à la coupe sont localisés au bout de la tête de forage et sont confinés dans une zone inaccessible à l'observation. Ainsi, une étude de ce procédé par une approche scientifique est proposée. L'évaluation de la morphologie des copeaux est réalisée. En effet, c'est une bonne indication de la stabilité de la coupe et peut aider à choisir les conditions de coupe optimales. Des paramètres adéquats ont été proposés. La fragmentation des copeaux est parmi les phénomènes analysés. Dans ce sens, des essais de forage ont été réalisés. Les copeaux ont été triés selon leur morphologie et leur origine. Par la suite, les paramètres physiques proposés ont été évalués. L'analyse quantitative et qualitative des copeaux a permis d'identifier l'impact de la vitesse de coupe et de l'avance par tour sur le processus de coupe.

Mots clefs : **Forage profond BTA, essais de forage, morphologie/fragmentation des copeaux, analyse quantitative**

1 Introduction

Deep hole drilling is a particular case of drilling processes for machining holes with length-to-diameter ratio great than five. Several technologies with main characteristics based on the surface roughness and straightness of the hole are available. Among them the BTA technology stands out as a technology enables to perform deep holes, up to 1000 mm and more, with high productivity. The application fields of this technology are numerous, such as aeronautics, naval, automotive and nuclear. Since the origin of its development by Beisner during the 40s [1], deep hole drilling, which is also by BTA system, did not follow the same technical evolutions and did not arouse the same scientific interests as other machining processes. The scientific production about BTA deep hole drilling remains relatively (e.g. [1]-[5]). This can be explained by the exclusive industrial use of this technology that remains marginal compared to turning, milling or conventional drilling. An important part of the basic concepts of conventional drilling applies to cases of deep hole drilling. Indeed, this is a machining in a confined environment. Nevertheless, the deep hole drilling with the BTA technique has its cutting specificities. The tool confinement in the workmaterial associated with high length of the hole give it as well as to the workpiece environment extreme operating conditions in terms of thermomechanical loading. In deep hole drilling the combination of chip removal, lubrication and localization of the thermomechanical loading in a confined cutting zone has a direct impact on the tool life and machining performances. The main treated problems concern the following topics: the role of guide pads, the dynamic phenomena occurring during the machining and the chip formation process.

Analysis after machining of the BTA deep hole drilling process by examining the chips morphology allows understanding the cutting process and therefore helps to choose optimal cutting conditions. For instance, analysis of the chips morphology in various machining processes has been conducted in several studies (e.g. [7]-[11]). Serrated, segmented or fragmented chips are very suitable chips characteristics to reduce solicitation of the cutting tool and facilitate chips evacuation, particularly in drilling process where chips removal occurs in confined zone. Usually the chip morphology is quantified by the classical parameter, known as the chip compression ratio [10], which is an indicator of the amount of plastic strain in the chip. Recently, Atlati et al. [8] have introduced a new parameter, called segmentation intensity ratio based on the evolution of the plastic strain along the chip length, and Kouadri et al. [9] other parameters based on dimension characteristics of the chip to quantify the chip segmentation phenomenon, and explain ([8], [9]) with these parameters the cutting force reduction with cutting speed increase. Therefore, analysis of the chips morphology obtained with the BTA deep hole drilling is an interesting way to characterise the cutting process after machining.

The objective of this paper is to characterise the BTA deep hole drilling process after cutting operation by an analysis, qualitatively and quantitatively, of the chips morphology at the macro and micro scales. The experimental procedure is developed, describing the workmaterial, the drilling machine, the BTA drilling tool and performed drilling tests. Parameters for the assessment of the chip morphology to be applied for the analysis of the chip formation process in the BTA deep hole drilling are described. Two analyses are performed, one is based on the macro and microscopic observations of chips generated by the central, intermediate and extern inserts of the BTA drilling tool, and the other is based on the assessment of the defined parameters, which are based on dimension characteristics of generated chips. Consequently, the impact of cutting conditions on the performance of the BTA deep hole drilling process when machining a low alloy steel has been highlighted. Chip Fragmentation Ratio as new parameter is introduced for this purpose. Using this parameter, as an indicator of chips size, the risk of chips blockage in the boring bar channel has been discussed. In order to identify an optimal range of cutting conditions for the considered tool/workmaterial couple, a discussion has been given based on obtained results about the chips morphology and the risk of an excessive tool wear.

2 BTA deep hole drilling tests

In order to analyze the cutting process in the BTA deep hole drilling, experimental tests are performed. Drilling tests are performed on machining center with horizontal multi-spindles. The machining centre is equipped with numeric command and has a stroke of about 1m in the axial (feed) direction. The used drilling technique is shown in Figure 1(a) and the drilling tool is shown in Figure 1(b) and (c). The workpiece material is a bainitic low alloy steel, an iron-carbon based-steel, essentially used for the construction of reactors vessels of nuclear power plants. The methodology used for the experimental design, for the considered tool-workmaterial couple, consists two vary two cutting parameters (cutting speed and feed rate).

It aims to define experimentally, for the considered cutting process, the optimal or stable range of cutting conditions for a given tool-workmaterial couple. Performed deep hole drilling tests are reported in Table 1. The range of variation of cutting parameters was chosen based on cutting conditions recommended by the tool manufacturer [12] for the particular case of this machining process.

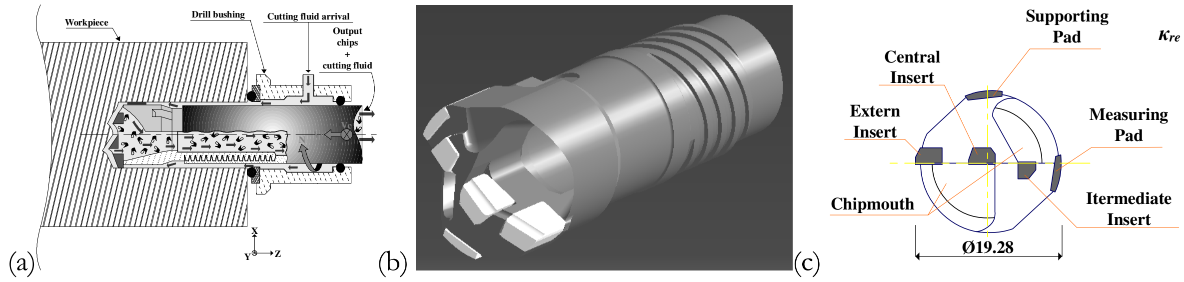


FIG. 1 – (a) Schematic representation of the deep hole drilling with BTA-STS system, (b) BTA deep hole drilling tool and (c) main parts of the drilling tool.

Table 1. Experimental design: hole length of about 300 mm.

N° test	Cutting speed [m/min]	Feed rate [mm/rev]
1	65	
2	80	
3	95	
4	110	0.145
5	125	
6	140	
7	155	
8		0.1
9		0.13
10	120	0.155
11		0.165
12		0.175
13		0.19

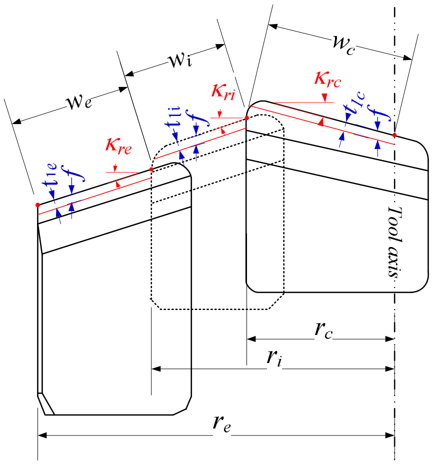


FIG. 2 – Engaged cutting edge width (w) and undeformed chip thickness (t_1) of each insert of the BTA deep hole drilling tool.

3 Chip morphology parameters

Analysis of the chips morphology enables to understand the cutting process, particularly in drilling processes. This gives indications about the stability of the cutting process. Indeed, for deep hole drilling processes this is more justified because the chip formation occurs in confined environment where the cutting zone is not accessible to the observation by the available experimental means. Literature review reveals that very few research works are dedicated to the analysis of the chip formation in deep hole drilling process (e.g.[10]). Hereafter chips morphology parameters based on dimension characteristics of generated chips are introduced for this purpose.

The first chip morphology parameter is the engaged length of the cutting edge of each insert of the BTA drilling tool, see Figure 2, given by

$$w_c = r_c \cos^{-1}\left(\kappa_{rc}\right), \quad w_i = \left(r_i - r_c\right)\cos^{-1}\left(\kappa_{ri}\right), \quad w_e = \left(r_e - r_i\right)\cos^{-1}\left(\kappa_{re}\right) \tag{1}$$

The second one is the well-known chip compression ratio, defined as follow

$$CCR = t_2 / t_1 \tag{2}$$

In the case of deep hole drilling, as suggested e.g. by Astakhov and Shvets [10], the mean chip thickness can be assessed by the weight method. By the knowledge of the chip mass (m_c), the chip length (l), the chip width (w) and the workmaterial density (ρ), t_2 is then deduced from the relationship:

$$t_2 = m_c / \rho w l \tag{3}$$

As mentioned in the introduction, the chips size has an impact on the chips evacuation. Smaller chips are easily evacuated by the cutting fluid. Hence it is interest to propose an adequate parameter quantifying the chips size. A new parameter denoted Chip Fragmentation Ratio (CFR) is then proposed in this study. The CFR parameter is defined as the ratio of chip length (l) by undeformed chip thickness (t_1):

$$CFR = l / t_1 \tag{4}$$

where the chip length (l) is evaluated by the weight method as follow

$$l = m_c / \rho w t_2 \tag{5}$$

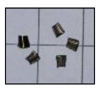
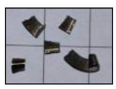
4 Results and discussion

The BTA deep hole drilling tests are mainly analyzed from the chips morphology characterization. Macroscopic and microscopic observations of generated chips are performed. The influence of cutting conditions on the cutting process is highlighted using the defined chip morphology parameters. The analysis and interpretation of the obtained results should give some indications about optimal cutting conditions for the considered tool-workmaterial couple.

4.1 Characterization of chips and their provenance

For each drilling test, chips with different shapes are obtained. The first step of the analysis is to separate these chips from their provenance, as shown in Table 2, i.e. identify chips generated by each insert (central, intermediate and extern inserts). Indeed, the particular geometric and kinematic configuration of the BTA deep hole drilling (position, inclination and tangential cutting velocity of inserts) has a direct effect on generated chips morphologies. As shown in Table 2, the central insert generates spiral chips which can be identified easily. This spiral shape is the consequence of abrupt change of the cutting speed along the engaged cutting edge of the central insert (tangential cutting velocity changes from zero to a certain value). While intermediate and external inserts generate more open chips which is more difficult to distinguish at first view.

Table 2. Generated chips for one cutting test. (Test n°1 : Vc = 65 m/min, f= 0.145 mm/rev)

Generated chips	Chips sorted by insert		
	Central insert	Intermediate insert	Extern insert
			

4.2 Quantitative analysis of the chip morphology

4.2.1 Chip compression ratio

The CCR parameter enables to quantify the average plastic strain occurring in the removed layer of the workmaterial, and therefore gives an insight about the consumed cutting energy per insert. The CCR parameter is assessed using the measured chip thickness and the undeformed chip thickness, as shown in Figure 3. From Figure 3(a), CCR as function of the cutting speed is higher for central and intermediate inserts. This is due to the fact that for specified rotation speed of the BTA drilling tool, the average tangential cutting speed is different between inserts (inserts penetrate in the workmaterial with different velocities). As stated by Astakhov and Shvets [10] and Kouadri et al. [9], CCR generally decreases with the increase of cutting speed. This corroborates results shown in Figure 3(a). Noting that for the extern insert CCR seems quasi-independent of the cutting speed. This suggests that there is a certain amount of cutting speed beyond it there is a little influence on the chip thickness. With the variation of the feed rate, as shown in Figure 3(b), the extern insert penetrates in the workmaterial always with higher cutting speed than the intermediate insert and then the central insert. This result is also coherent with the work of Kouadri et al. [9]. In summary, for a given cutting conditions (rotation cutting speed and feed rate) the amount of plastic strain in chips generated by the extern insert is the lower (higher cutting speed).

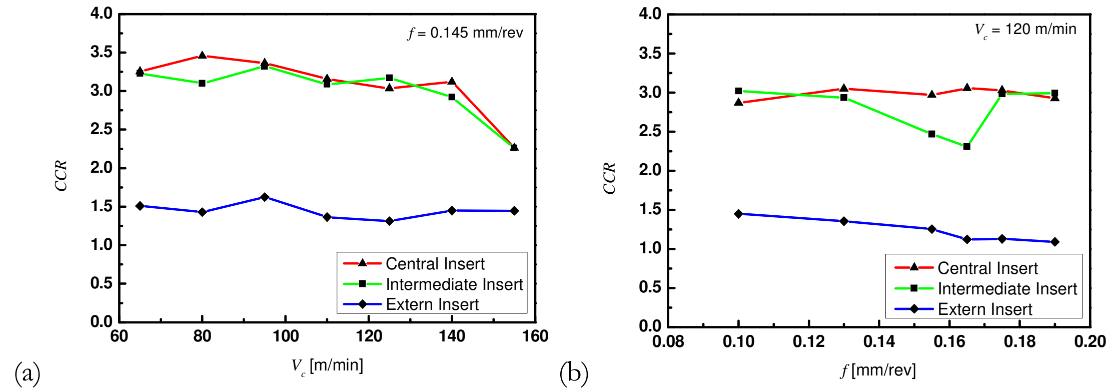


FIG. 3 – Chip Compression Ratio as function of (a) cutting speed and (b) feed rate.

4.2.2 Chip fragmentation ratio

Since the chips length is related to the fragmentation process of chips under specified cutting conditions, the proposed chip fragmentation parameter (CFR) is then evaluated, giving a quantitative evaluation of the chip fragmentation phenomenon. It is shown that the CFR as function of the cutting speed, for the fixed feed rate (0.145 mm/rev), evolves as for the chip length, see Figure 4(a), while CFR as function of the feed rate, for fixed cutting speed (120 m/min), decreases for all chips generated by the three inserts of the BTA drilling tool, see Figure 4(b). Clearly, the chip fragmentation phenomenon is more affected by the feed rate than by the cutting speed. This corroborates ascertainment of the tool manufacturer [12], which suggests that shorter chips are obtained by increasing the feed.

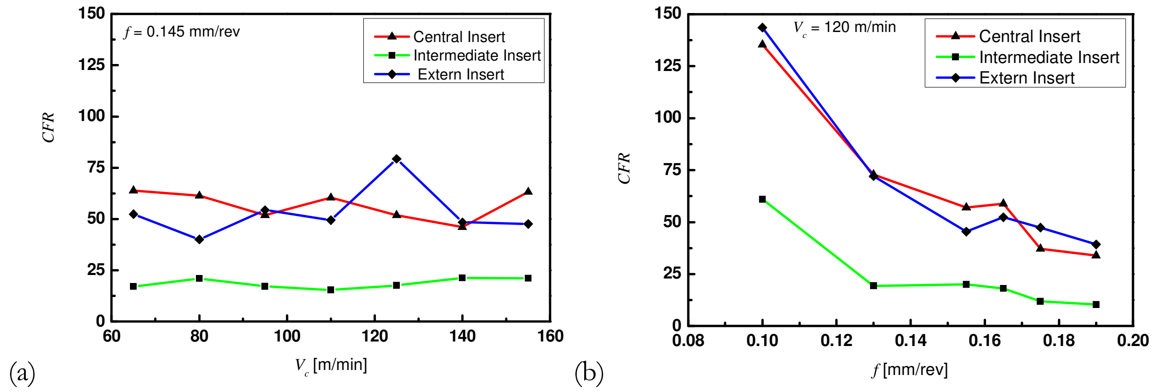


FIG. 4 – Chip Fragmentation Ratio as function of (a) cutting speed and (b) feed rate.

5 Concluding remarks

The BTA deep hole drilling process has been analyzed based on the characterization of the cutting operation after machining. A quantitative analysis using adequate parameters has been proposed. Macroscopic observations of generated chips has not allowed to highlight the impact of cutting conditions on the cutting process, since chips size, as function of cutting speed or feed rate, are difficult to distinguish at this scale. Hence a quantitative analysis based on geometrical characteristics of chips, using adequate parameters (chip width, chip length, chip compression ratio and chip fragmentation ratio), is shown more interest. It is shown that the influence of the cutting speed and feed rate on the chips width is very negligible and the last one can be approximated geometrically. This concludes that the chip formation occurs under plane strain condition. The assessment of the chip compression ratio, as an indicator of the amount of plastic strain in generated chips, has shown that increasing the cutting speed the CCR for chips generated by the central and intermediate inserts decreases and for chips generated by the extern insert the CCR remains quasi constant. While increasing the feed rate the CCR fluctuates around a fixed value for each set of chips generated by inserts. Using the chip fragmentation ratio, it has been shown that the chip fragmentation is highly influenced by the feed rate and quasi-independent of the cutting speed for the considered tool-workmaterial couple. Increasing the feed rate decreases the chip length, which facilitates the chip evacuation. However the feed rate should not be increased excessively, since higher values generates higher solicitation on the BTA drilling tool, which may even leads to an excessive tool wear and in extreme case the locking of the BTA drilling head in the hole. As a future work, it is interest to establish a correlation between the chip fragmentation and the hole surface quality. Finally, the proposed methodology can be applied for other cutting processes.

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